THE ELECTRIC STRENGTH OF AIR AT ATMOSPHERIC PRESSURE UNDER ALTERNATING AND CONTINUOUS POTENTIALS.

DISSERTATION

Submitted to the Board of University Studies
of the Johns Hopkins University in con-
formity with the Requirements for the
Degree of Doctor of Philosophy

By

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June, 1916,

I N D E X

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Contents

I

INTRODUCTION

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(1) Importance of the study of the high voltage corona: The name "corona" was first used by Steinmetz[1] to describe the glow which appears around conductors carrying very high voltages either alternating or continuous. A loss is associated with this phenomenon which begins at a voltage depending on the physical constants of the circuit and on atmospheric conditions. In the case of very high voltages and long conductors both of which occur in modern transmission lines, this loss becomes of serious magnitude which fact has prompted its investigation by Steinmetz[1], Scott[2], Ryan[3], Mershon[4], Jona[5], Peek[6], Whitehead[7], Bennett[8], Farwell[9] and a number of others.

(2) Review of previous work: The alternating current case has been the principal subject of research as most high voltages used in engineering practice today are alternating. Among recent investigations of the alternating current corona those of Whitehead and Peek have been the most important, because of the improvements in the experimental methods used and the thoroughness with which the work has been carried out. Whitehead has for the most part investigated the conditions governing the beginning of corona while Peek has made extensive studies of the losses above the critical or corona-forming voltage.

The nature of the influence of a number of factors

governing the beginning of corona has been agreed upon generally by all the investigators. They have found that the voltage at which corona starts is independent of the material of the wire, of the moisture content of the air, of the presence of moderate ionization produced by artificial means, of the wave form and, between wide limits, of the frequency. Further, that it is a function of the wire diameter, of the distance, shape and position of the opposite conductor, of the temperature and the atmospheric pressure.

The term "surface intensity" is frequently used in expressing the results of investigations on corona and signifies the intensity of electric force, i.e., the potential gradient at the surface of the corona forming conductor. In the case of a wire and coaxial cylinder it is given by the expression:-

$$E = \frac{V}{a \log_e \frac{b}{a}} \qquad (1)$$

where, E = surface intensity in volts per cm.

V = maximum value of the potential difference between the wire and cylinder, in volts.

a = radius of the wire in cms.

b = " " " tube " "

In the case of two parallel wires,

$$E = \frac{V}{2a \log_e \frac{d}{a}} \left(1 + \frac{a}{d}\right) \qquad (2)$$

where, d = distance between the wires.

The first of these formulae is exact, the second approximate. When a is small compared with d and the wires are well

above the earth, the second formula gives the value of E within a very small error.

Alexander Russell[10] using Whitehead's observations found that the relation between the value of the surface intensity at which corona appeared, now generally termed E_c the "critical surface intensity", and the diameter of the wire at standard atmospheric conditions could be represented by an equation of the form,

$$E_c = A + \frac{B}{\sqrt{d}} \qquad (3)$$

where, E_c = critical surface intensity generally stated in kilovolts per centimeter

d = diameter of the wire in centimeters

A & B = constants

The observations of Whitehead gave A = 32 and B = 13.4. The work of Peek somewhat later showed a similar relation between E and d, giving A = 29.8 and B = 12.7. These values in his subsequent papers have been brought up to 31.0 and 13.5 respectively, which are in close agreement with the results of Whitehead.

Peek first showed that the influence of temperature and pressure could be included in one term called the "density factor",

$$\delta = \frac{3.92 \times p}{273 + t} \qquad (4)$$

where, p = pressure in centimeters of mercury

t = temperature in Centigrade degrees.

This is in accord with the kinetic theory and also the present theories of gaseous conduction in which the density of

the gas as influenced by either temperature or pressure is a determining factor in conduction and spark discharge. It will be noted that δ has the value 1 for p = 76 cm. and t = 25° C. The general formula covering the variations of critical intensity with change of temperature and pressure for a tube and concentric wire, as given in one of Peek's later papers, is as follows:-

$$E = 31\delta\left(1 + \frac{0.308}{\sqrt{\delta r}}\right) \qquad (5)$$

where, E = critical intensity in kilovolts per centimeter

r = radius of the wire in centimeters

δ = density factor

(3) <u>Outline of the theory of secondary ionization:</u> Townsend[11], using the theory of secondary ionization, has deduced a theoretical formula connecting the intensity, E, the pressure, p, and d, the diameter of the wire, on the basis of the assumptions that spark discharge may be explained by the theory of secondary ionization, that corona is a form of spark discharge and that the electric intensity at the outer boundary of corona is 30 kilovolts per centimeter, the minimum value of the sparking intensity for air, as observed between parallel plates, and that the average intensity in the corona is $\frac{X_1 + 30}{2}$, where X_1 is the intensity at the surface of the wire. Equating this last expression to that for the intensity required to pass a spark between parallel plates at a distance S apart, 30S + 1.35 (6), and putting S = c - a, where a = radius of the wire and c = radius of corona, we have

$$\frac{X_1 + 30}{2} = 30 + \frac{1.35}{c-a} \qquad (7)$$

The intensities at any points outside of the wire vary inversely as their distances from the center of the wire, or $\frac{c}{a} = \frac{X_1}{30}$ and $c = \frac{X_1 a}{30}$, which when substituted for c in equation (7) gives, when the equation is solved for X_1.

$$X_1 = 30 + \frac{9}{\sqrt{a}} \qquad (8)$$

Townsend's theory shows that Xa is a function of pa, where p is the pressure and X and a have the values already stated. As $X_1 = 30 + \frac{9}{\sqrt{a}} = 30a + \frac{9a}{\sqrt{a}}$, we can also write,

$$X_1 a = 30pa + \frac{9pa}{\sqrt{pa}} \qquad (9)$$

or,

$$E = X_1 = p(30 + \frac{9}{\sqrt{pa}}) \qquad (10) \quad \text{(Townsend)}$$

where, E = critical intensity in kilovolts per centimeter

p = pressure in atmospheres

a = radius of the wire in cms.

If the values of E as obtained from the empirical formulae of Whitehead and Peek and from the results of some of the other investigators of the alternating current corona be plotted as a function of the radius of the wire, we find that the value of E for any one wire shows noticeable discrepancies. The differences in the observed values are probably due to the difficulty in measuring the ratio of maximum to effective values of the high voltage, to the unequal surface condition of the wires and to failure to properly correct for atmospheric conditions.

The most important work on the direct current corona has been done by Watson[12], Schaffers[13] and Farwell[9], Watson made

observations with wires ranging from 0.70 mm. to 12.76 mm. in diameter, using as a source of power an influence machine of special design. For the case of a wire and cylinder he found that the polarity of the wire had a marked influence on the appearance of the corona and in the value of the critical intensity. Schaffers using wires from 0.0006 - 0.70 cm. in diam. in tubes of various sizes found that for the larger size wires the positive corona appeared at a lower voltage than the negative while for the smaller sizes the reverse was true. The curves of critical intensity crossed at a point corresponding to a wire 0.01 cm. in radius. Farwell, using a series of 500 volt generators as a source of high potential, investigated the influence of the polarity of the wire, of temperature, pressure and humidity on the corona-forming voltages on copper wires ranging from 0.0038" - 0.1019" in diameter in a tube 4.45 cm. in diameter. For a given size wire, he found that corona appeared at a much lower voltage when the wire was positive. His observations can be represented by formula (3) and the value of the constants as given in his A.I.E.E. paper are for the positive wire, A = 31.6, B = 8.47, for the negative wire, A = 35.0, B = 8.06. Here again, as in the alternating current case, the results of different investigators show considerable divergence.

(4) Object of the present investigation: It was in view of these differences among the values of each type and between the two types that the present investigation was undertaken. The different conditions under which these investigators work-

ed should account in a large measure for the different values obtained for both alternating and continuous voltage. The aim of the present experiments has been to compare alternating and continuous values of corona voltage under identical conditions and under the best possible conditions for accuracy.

Some later experiments outlined in section V had as their purpose the checking up of some of the assumptions of the present day theories as to start and ultimate nature of corona.

II

DESCRIPTION OF APPARATUS.

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(1) <u>The apparatus for the production of and measurements on the alternating current corona:</u> The diagram of connections for the production of and measurements on the alternating current corona is given in fig. 1. The motor generator, G, supplies the low tension winding of the transformer, T, through a potential regulator, P.R. One terminal of the high tension winding is connected to the low tension winding and to ground and the other to the corona wire. C.T. is the corona tube and E, an electroscope, both described in detail in a subsequent paragraph.

(a) <u>The Generator</u>

The motor-generator set consisted of two 5-k.w., 1200 r.p.m., 120 volt alternating current generators, one 60 and the other 25 cycles, driven by a 7.5 h.p., 120 volt direct current, shunt wound motor. The use of a storage battery of large capacity as a source of energy for driving the motor and for exciting the two alternators made it possible to obtain a very constant voltage. Throughout the experiments only the 60 cycle unit was used.

(b) <u>The Transformer</u>

The transformer used was rated at 3000 watts, 60 cycles, 100-25000 volts. The low tension winding was in two 50 volt sections, the high tension in four 6250 volt sections. The ratio of terms of the transformer as furnished by the manu-

facturer was 1-250.18 and this ratio was used to determine the secondary voltage. The primary voltage was read on a standardized Weston dynamometer voltmeter, V, (Fig. 1) and was controlled by the potential regulator, P.R. and a variable resistance, R, in the generator field, F. The influence of the varying IR drop in the primary winding was practically negligible in its effect on the ratio of transformation owing to the small values of the magnetizing and load currents. This was shown by Whitehead in one of his earlier papers by inserting resistance in series with the primary of the transformer used in this investigation and noting the influence on wave form and corona voltage.

(c) The Corona Apparatus

The corona apparatus consisted of a wire stretched coaxially in a metal tube. The wire was clamped at each end in a device which permitted of stretching and centering. The tube was mounted on an insulated stand, which also supported a very sensitive electroscope. Small holes were drilled in a section of the tube and a disc of the same curvature as the tube was connected to one terminal of the electroscope and placed as close to the tube as possible without actual contact. The disc, the connections to the electroscope and the electroscope proper were protected by grounded metal shields. The electroscope was charged to a potential of 440 volts from the lighting mains through lamps and condensers as shown in fig. 2. With switches S_1 open, S_2 closed and S_3 up the condensers, C_1 and C_2, are charged in parallel at 220 volts.

With S_1 open, S_2 open and S_3 down, the condensers are thrown in series and the electroscope is charged. When S_1 is closed to ground, the condensers are discharged. The insulated stand was grounded for the alternating current observations thus grounding the other terminal of the electroscope. The ionization accompanying the very first appearance of corona causes the electroscope to discharge rapidly, which thus served as a detector of corona. Fig. 7 is a photograph of the tube as used in some later experiments.

(2) The apparatus for the production of and measurements on the continuous-current corona:

(a. The high voltage generator method): Two sources of high continuous potential were available, a high-voltage generator and a "kenotron"[14] or hot-cathode rectifier. The diagram of connections in the use of the former is shown in fig. 3. G, the generator, supplies the high potential through parallel condensers, C, to the corona wire. V, M and G' are a voltmeter, multiplier and galvanometer respectively.

(1) The High-voltage Generator

The generator of special design, manufactured by the Holtzer Cabot Company, consisted of eight units mounted on an insulating bed. Each armature was provided with two windings and commutators and was rated as follows:- Amperes = 0.1; speed, 2700 r.p.m.; volts per commutator, 937.5; shunt wound. The available potential was, therefore, 15000 volts, when the machine was run at normal speed and all the units in series.

The connection of a large number of low voltage generators in series as a method of obtaining high values of continuous potential has been used in a great many cases. The generators were separately excited and insulation became proportionally more difficult as the number of units in series (hence the voltage) was increased, break down usually occurring through the common field circuit. In the present case self-excited, shunt-wound generators were used with individual rheostats mounted on each frame and special precautions were taken in the design of the insulation. The generators were driven by a 5 h.p., 220 volt, direct current, shunt-wound motor through an insulating belt and insulated couplings. Voltage control was obtained in two ways. Adjustable carbon rod resistances connected in series with the generator fields and carefully insulated from the frame were mounted on the top of each machine and a moveable insulated gearing provided uniform variation of all the rheostats. For fine adjustment a rheostat was inserted in the driving motor field which gave voltage control by varying the motor speed. A photograph of the entire unit is given in fig. 8 and a diagram of the internal connections in fig. 4.

(2) <u>The Condensers</u>

The condensers, whose function will be explained later, were of the Moscicki type, insulated for 20000 volts, effective value. These condensers are of the Leyden jar type, the dielectric being of glass and to prevent corona from forming

on the edge of the plates, the condensers are filled with oil. Two condensers were used, each consisting of eight units of 0.002 m.f. capacity.

(3) The Instruments

The voltmeter was a Weston of the permanent magnet type, with two scales (0-150 and 0-750 volts). It was carefully compared throughout its entire range with a Weston Laboratory Standard instrument and found correct within the limit of observation error, i.e., 0.1%. The resistance of the high scale winding was 82790 ohms. As it was desired to measure potentials of the order of magnitude of 35000 volts, a multiplier of 4.5 megohms was necessary. Shunting the instrument by an approximately equal resistance reduced this amount by one-half although it introduced the disadvantage of doubling the power required. For example,at 15000 volts this demand is 0.0065 amperes and is great enough to impose a serious limitation on some of the later experiments. A number of multipliers of the regular type supplied by the Weston Company for increasing the range of their laboratory voltmeters were available. Their total resistance, however, was only 707,630 ohms. To obtain the remaining amount of resistance required, six units were made up in this laboratory according to specifications of the Bureau of Standards. Each unit consisted of forty mica cards wound with manganin wire. The resistance of each card was approximately 6000 ohms. They were mounted on horizontal glass rods, which in turn were supported by hard rubber uprights, and the whole mounted on

a hardwood base. The current-carrying capacity was 0.022 amperes. The resistance of each unit was measured by means of a Wheatstone Bridge and also by placing them in series with a standard Weston voltmeter of known resistance across mains of known potential. A photograph of a complete unit is shown in fig. 9.

(<u>b. The kenotron method</u>): The diagram of connections for the second method is shown in fig. 5. G, the high-frequency generator supplies, through the grounded transformer, T, the kenotron, K, with high voltage. The condensers C_1 and C_2 and the inductance, L_2 are introduced to smooth out the voltage which is rectified in pulsating form by the kenotron. M and V_2 are the multiplier and voltmeter as used in the first method and C.T. is the corona tube, with the electroscope, E, and the galvanometer, G, as before. L_1 is an inductance, V_1, a hot-wire voltmeter and A_1 a hot band ammeter. Voltage control was obtained by varying the field circuit of the generator by means of the resistance R_1.

(1) <u>The High-frequency Generator</u>

The high-frequency generator was a direct-driven unit consisting of a generator with a double field structure, one of 48 poles, the other of 240, and a 3 h.p., 240 volt, direct current shunt wound motor. The armature of the generator was stationary and provided with a distributed winding. The rated full speed was 1500 r.p.m., at which one generator gave 600 cyles and the other 3000. The genrators were rated at 4.4 amperes and 110 volts.

Speed or frequency control was obtained by armature and field resistance in the motor circuit, the use of the former being practically limited to starting. The driving motor and the generator field were both supplied from a storage battery which made conditions very favourable for steadiness in readings. Fig. 10 is a photograph of the complete unit.

(2) The Kenotron

It has been known for a number of years[15] that an exhausted tube containing two electrodes, one of which is heated by an external source acts as a rectifier. In order that the conductivity of such a device be absolutely unidirectional it is essential that the only carriers of electricity present be electrons, i.e., elementary negative ions. In the earlier types of rectifier such as that of Wehnelt employing a hot-lime cathode as a source of electrons, the currents obtained were due in a large measure to positive rather than negative ions as carriers. Under the degree of vacuum used, the magnitude of the current varied greatly and the cathode rapidly disintegrated under bombardment by the positive ions limiting the applied difference of potential to a few hundred volts.

The rectifier has been developed in its improved form[14] by the Research Laboratory of the General Electric Company, and is known as the"kenotron" (kenos, meaning empty, tron signifying an instrument or appliance). In its present form the difficulties met with in the earlier types have been entirely overcome. Intense heating of the bulb and all metal parts during the process of exhaustion serves to make the

rectifier practically free from gas. By exhausting the tubes to a very low degree of vacuum the mean free path of an electron is made so great that its chance of colliding with any gas molecules still present and thereby forming positive ions is reduced to a minimum. Under these conditions electrons only are present, the current obtained is constant in magnitude, the life of the cathode is materially increased and very high potentials may be applied to the tube when properly designed.

The "thermionic current" from a hot cathode is limited by temperature and by "space charge". Tungsten filaments serve as cathodes and the temperature (hence, the electron emission) is dependent upon the current through the filament as furnished by an auxiliary source for heating only, such as a battery. The electrons emitted from the hot cathode and filling the space between the electrodes produce an electrostatic field which tends to prevent the motion of electrons toward the anode by lowering the potential gradient. As the positive potential of the anode is increased, however, the potential gradient becomes greater and greater and more and more electrons reach the anode or the thermionic current flowing is increased. The effect of temperature and this space charge is clearly shown in fig. 6, which represents the results observed when the thermionic current was measured from a 10- mil tungsten filament in the axis of a cylindrical anode 7.62 cm. long and 1.27 cm. in radius, in which the thermionic current is plotted as a function of the temperature.

As the temperature of the cathode is increased the electron emission increased at first in accordance with the well-known law of Richardson, expressing the relation between the thermionic current and the temperature of the cathode. This law is $i = a\sqrt{T}e^{-b/T}$ (11)

where i = current per sq. cm. of cathode

T = absolute temperature

e = base of Naperian system of logarithms

a & b = constants

Upon further increasing the temperature of the cathode a point is reached at which the current becomes constant, or further increase in temperature does not produce any corresponding increase in current, owing to the reverse gradient imposed by the space charge. The point at which this limitation occurs varies with the potential of the anode. With a potential difference of 55.5 volts, Richardson's law was obeyed up to about 2300° K. and beyond this point the current became constant. At 87.5 volts potential difference, the thermionic current increased up to 2350° K. and at 129 volts, the increase in thermionic current was observed up to 2400° K.

The kenotron used in the present investigation was known as #152 and was designed for a maximum voltage of 40000. It consisted of a highly evacuated glass bulb containing a cylindrical anode along whose axis was stretched a 10- mil tungsten filament, which acted as the hot cathode. The cylindrical anode was of small diameter in order to bring the anode and cathode very close together to reduce the space

charge effect and thereby increase the current carrying capacity of the rectifier. One terminal was of the ordinary incandescent lamp filament type and served to supply energy to the cathode, acting at the same time as one terminal for the high voltage. The other end of the tube was sealed off with a metal cap and ring, which served as the other high voltage terminal.

For heating the tungsten filament a 12- volt storage battery, (B, fig. 5) was used. A resistance, R_2, a 15- amp. ammeter, A_2, and a knife switch, S_2, were connected in series with the battery to provide control of the filament current and indirectly the electron emission. The table below gives the electron emission and the voltage drop in the kenotron for various filament currents. A filament current of 6.5 amperes was used throughout this work, as this amount of current was found sufficient to give the required electron emission.

TABLE I

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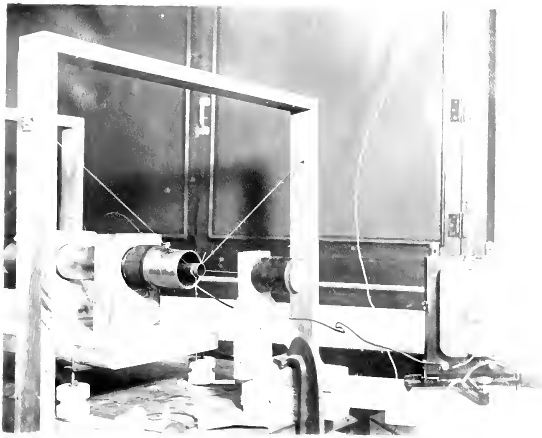
Characteristics of the Kenotron

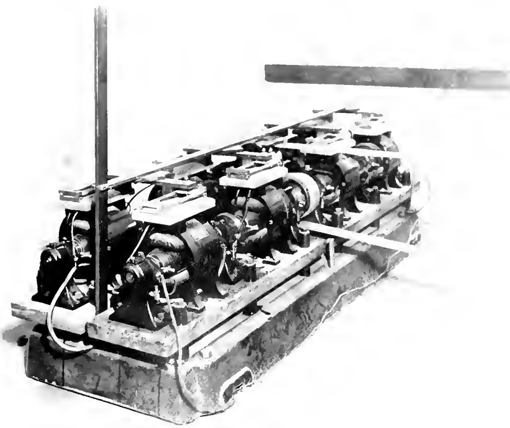
Filament Current	Electron Emission	Minimum Voltage Drop
5.0	9.5	--
5.2	16.0	86
5.4	27.0	122
5.6	40.0	158
5.8	57.0	200
6.0	82.0	250
6.1	100.0	280

(3) The Condensers and Inductances

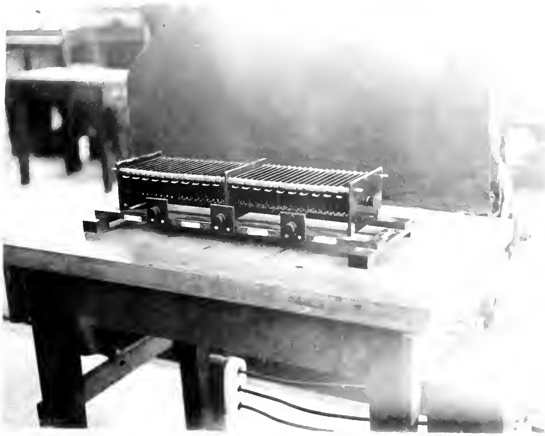
The capacity, C_1 (Fig. 5), was made up of six units connected two in series, three in parallel. Each unit was insulated for 10000 volts and had a capacity of 0.01 m.f. The condenser plates were immersed in oil. Corona gaps set for 10000 volts were placed across the terminals of each unit to prevent breakdown of the insulation resulting from possible unequal distribution of potential. The capacity, C_2, was made up of four similar units connected two in series, two in parallel together with the Moscicki condensers used in connection with the first method. The inductance, L_1, consisted of two air coils of 360 turns of #10 B. & S. wire. The coils were in parallel but magnetically insulated from each other. On 600 cycles they had an impedance of 9 ohms each. The high tension winding of a 5 k.w.,6600/110 volt, 60 cycle Westinghouse power transformer served for L_2. The function of these inductances is explained in connection with the experiments.



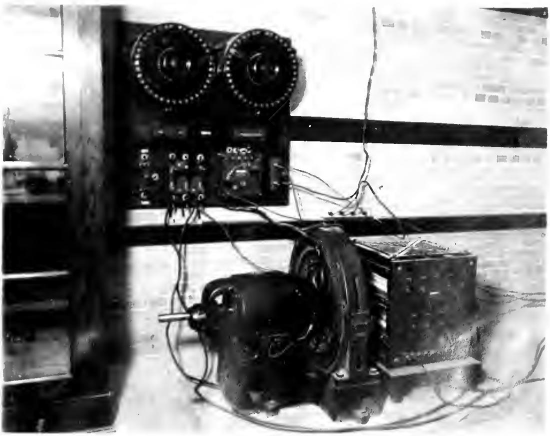
Corona Tube
Fig.-7



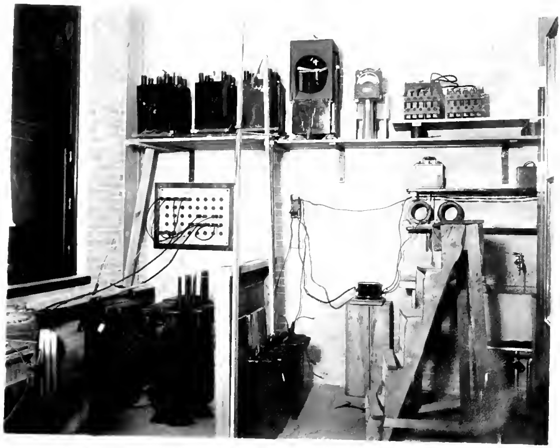
High-voltage Generator
Fig-8



Resistance Unit
Fig-9.



High Frequency Generator
Fig.-10



The Kenotron

Fig.-11

III

PRELIMINARY EXPERIMENTS

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(a) Calculation of approximate sizes of tube and wire to produce corona at the voltages available: On undertaking this investigation the approximate sizes of wire on which corona would appear for both alternating and continuous current with tubes of a given diameter were first calculated from the results of previous researches. Two tubes were used, with inside diameters of 6.109 and 4.855 cm. respectively. Six sizes of wire were used with diameters of 0.074, 0.090, 0.125, 0.166 and 0.231 cms. All were of brass except the largest which was of steel. The wires were always carefully polished with crocus cloth and chamois before introducing them into the tube.

(b) Determination of the amount of capacity needed to insure constant voltage in the case of the high voltage generator: The first tests made were with the high voltage generator as a source of potential. A number of runs were made on the same tube and wire and the voltage at which corona appeared, as determined by visual methods, the temperature and atmospheric pressure were recorded for each run. A few of the observations are given in the table on the next page.

The first column gives the number of the run, the second the voltmeter reading at which corona appeared. The third columns is obtained by multiplying the voltmeter reading by the multiplying factor (19.83) and the fourth from the rela-

TABLE 2

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Positive Corona

Run	Voltmeter Reading	Vis. Cor. Voltage V	Crit. Surf. Intensity E	Temp. Cen. Deg.	Press. Cm. Hg.	δ
#1	607.0	12037	67.2	22.0	75.8	1.007
#2	548.0	10868	60.7	21.0	75.6	1.008
#3	635.0	12592	70.3	26.0	76.9	1.007
#4	600.0	11898	66.5	23.0	74.7	0.989
#5	597.5	11848	66.2	24.5	74.4	0.987

Diam. Tube = 4.855 cm. Diam. Wire = 0.090 cm. $E = \frac{V}{a \log\frac{b}{a}} = \frac{V}{.1791}$

tion $E = \frac{V}{a \log_e \frac{b}{a}}$ (Formula 1). The fifth and sixth columns are the observed temperature and pressure and the seventh gives the value of δ as given by $\delta = \frac{3.92p}{273+t}$ (formular 4). The value of E varies greatly even in the first three runs where the effect of temperature and pressure is negligible (i.e., δ = constant). Each of these readings could be repeated again and again during the same run.

In the case of the alternating current corona it had been shown by Whitehead and others that the corona appears as soon as the maximum value of the wave reaches the value of E as based on the formula, $E = 32 + \frac{13.4}{\sqrt{d}}$, and further that corona appears for only momentary duration of this value. It was reasonable, therefore, to suspect that the above discrepancies might be accounted for by irregular inequalities in the continuous voltage, of frequencies not appearing in the

voltmeter reading. To test the constancy of the voltage an oscillogram (fig. 12) was taken which showed plainly its variable character. The central wave is the voltage of the entire set.

In an effort to smooth out the inequalities of voltage two Moscicki condensers (0.004 m.f.) were connected in parallel with the generator. The upper wave in the oscillogram (fig. 12), taken under these conditions, shows that the voltage fluctuation was increased. Sixteen Moscicki units (0.032 m.f.) were then used and the oscillogram (fig. 13) shows that the voltage was then practically constant. The frequency of the oscillations when two units were used, was obtained by superimposing a wave of known frequency as shown in the oscillogram (fig. 14). The upper wave has a known frequency of 54.5 cycles per second and the lower has two frequencies, a fundamental and a recurrent one. The frequencies as measured from the oscillogram are for the fundamental, 359.5 cycles per second and for the recurrent, 12.3 cycles per second. An effort was made to connect these frequencies with periodic recurrences due to the speed of the motor, the generators, the belt, number of commutator segments, etc., but without success. The fluctuation disappeared with increased capacity in parallel and is probably due to a resonance condition between the inductance of the armatures and the capacity of the circuit. The slow superimposed fluctuation could not be definitely traced. Further investigation of this interesting phenomena had to be postponed.

A determination of E as a function of the capacity in

parallel with the generator showed that above 0.016 m.f. the value of E was constant. The results are given in table (3) and are plotted in the form of a curve in fig. (15). A capacity of 0.032 m.f. was used,twice as much as actually required.

TABLE 3

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Apparent lowering of the critical surface intensity due to resonance in the generator circuit

No. of Units	Capacity m.f.	Voltmeter Reading	Critical Surface Intensity (E)
1	0.002	620	68.6
2	0.004	555	61.4
3	0.006	622.5	68.9
4	0.008	647.5	71.7
5	0.010	652.5	72.2
6	0.012	662.5	73.3
7	0.014	666.0	73.7
8	0.016	665.0	73.7
9	0.018	665.0	73.7
10	0.020	665.0	73.7
11	0.022	665.0	73.7
12	0.024	665.0	73.7
13	0.026	665.0	73.7
14	0.028	665.0	73.7
15	0.030	665.0	73.7
16	0.032	665.0	73.7

It must also be noted that the percentage variation in voltage as shown by the oscillogram is much greater than that actually obtaining under test conditions as the oscillograph requires a current nearly 25 times that taken by the voltmeter and corona tube and the fluctuation varies directly with the current taken from the condensers. Under test conditions therefore (i.e., voltmeter and tube connected) the voltage varia-

tion is only a very small fraction of one per cent.

(c) Determination of the amount of inductance and capacity needed in the case of the kenotron: The maximum voltage obtainable from the high voltage generator was 15000 volts so the kenotron was used for higher values. It was soon found that the transformer used imposed a serious limitation on the value of the continuous voltage obtainable by this means. At 600 cycles the high tension windings of the transformer took a charging current of 20 or 25 amperes and as the full load current of the 600-cycle generator was only 4.4 amperes, the speed and consequently, the frequency rapidly dropped on connecting the transformer. Although the internal reactance of the generator was considerable, the capacity of the high tension windings of the transformer was more than sufficient to overbalance it. Additional reactance connected across the primary of the transformer was the obvious way of reducing this current. A number of air coils of low resistance were tried and after a number of trials the two coils as described in an earlier paragraph were selected as they reduced the charging current to about five amperes and gave a maximum value of continuous voltage of 26500 volts.

The next step in the development of the kenotron method was to introduce parallel capacity in the direct current side of the Kenotron to smooth out the voltage by supplying energy to the load during the part of each cycle when the kenotron delivers no current. When operated alone (i.e., without condensers) the rectifier gave a continuous voltage which fluctuated between zero and a maximum with the frequency of the

impressed e.m.f. (600 cycles). Four 10000 volt condensers in series (0.0025 m.f.) were connected between the direct current side of the kenotron and ground. The oscillogram, (fig. 16), shows the character of the continuous current voltage with the above capacity. Nine condensers connected three in parallel, three in series (0.01 m.f.) were next tried. The oscillogram (fig. 17) shows the decided improvement. The attempt to produce further improvement in the voltage by this means was abandoned as it was evident that a far larger amount of capacity than was available would be required to obtain a voltage varying less than one per cent.

As the impedance of the load (the voltmeter and corona tube) was high, the current which flowed was very small. Under these conditions a moderate amount of series inductance (50 or 100 henrys) in conjunction with capacity offered a probable means of further improvement if employed in the manner shown in fig. 5, where the capacity is divided into two portions. The voltage fluctuation at the terminals of C_1 is an irregular shaped wave which consists of a fundamental with a frequency of 600 cycles per second and a number of higher harmonics. The inductance, L_2, and the capacity, C_2, offer a definite value of impedance to each of these higher frequencies. The higher the frequency the greater the impedance offered by the inductance L_2 or in other words the voltage wave is smoothed out by removing the higher harmonics. The current drawn by the condenser C_2 over the inductance L_2 stores up electromagnetic energy in the latter. When the voltage of the condenser starts to fall, due to the current drawn from it

by the load, the energy stored up by the inductance is delivered to the circuit and tends to maintain the voltage at the terminals of C_2 constant.

A number of inductances were tried in the position, L_2, and the sound in a telephone used as a measure of the degree of voltage fluctuation. (The intensity of sound in the telephone is proportional to the amplitude of the voltage fluctuation). The minimum sound in the telephone was obtained when one-half of the high tension winding of a 5 k.w., 6600/110 volt power transformer was used. The oscillogram (fig. 18) shows the effect of inserting the inductance. This final arrangement was used throughout the tests.

It is possible to calculate the percentage voltage fluctuation under test conditions, if it is assumed that it is directly proportional to the current. Referring to fig. 5 the values were as follows, when the oscillograph was in circuit:-

$$C_1 = \frac{3(0.01)}{2} = 0.015 \text{ m.f.}$$

$$C_2 = \frac{2(0.01)}{2} + 0.032 = 0.042 \text{ m.f.}$$

$$C = C_1 + C_2 = 0.015 + .042 = 0.057 \text{ m.f.}$$

$$= 5.7 \times 10^{-8} \text{ farads}$$

V = direct current voltage = 4700

δV = voltage fluctuation = 13.8% = 650 volts

(By measurements on oscillogram)

i_1 = oscillograph current = 0.024 amps

(By measurement)

i_2 = voltmeter current = 0.001 amps

(By calculation)

i = total current flowing when oscillograph is connected

$= i_1 + i_2 = 0.025$ amps

$\omega = 2$ x frequency = 2 x 600 = 1200

Hull[16] has shown that the voltage fluctuation (δV) at the terminals of C_2 may be expressed by the simple relation

$$V = \frac{8\pi i}{L_2\omega^3\left(C + \frac{1}{L_2\omega^2}\right)^2} \qquad (12)$$

where i, ω and C are as given above and L_2 is the magnitude of the series inductance in henrys. If we assume L_2 constant, (i.e., independent of the amount of current flowing for such low flux density in the iron of the transformer which was used as L_2), we can write

$$\delta V = Ki \qquad (13)$$

Let δV_a = voltage fluctuation when current i is flowing

δV_b = " " " " i_2 " "

Then, $\delta V_a = Ki$ (14) and $\delta V_b = Ki_2$ (15)

Dividing (14) by (15) and transposing,

$$\delta V_b = \frac{i_2}{i} \times \delta V_a \qquad (16)$$

$$= \left(\frac{0.001}{0.025} \times 13.8\right)\% = 0.5\%$$

= percentage voltage fluctuation under test conditions, (i.e., voltmeter and corona tube)

(d) <u>Comparison of the different methods of detecting the start of corona:</u> A comparison of the different methods of detecting corona was then made. In the case of the alternating current corona the visual and electroscope methods were compared. The curves (fig. 19) show how closely the two methods

agree, when the bend in the electroscope curve is taken as the point at which corona forms. In the case of the direct current corona an additional method was available, i.e., a galvanometer connected between the tube and ground as used by Farwell and Mackenzie[17]. A ballistic galvanometer with a sensitivity of 10^{-6} amperes per mm. scale division when the scale was placed 1 meter from the mirror, was used. Below corona voltage if the wire were clean the galvanometer stood practically on zero. With the appearance of corona the galvanometer took a large deflection (5 to 10 cm.) and any further increase in voltage threw the light-spot off the scale.

The condition of the surface of the wire when fairly clean had but little effect on the value of the critical surface intensity in the case of the wire at positive or alternating current potentials, but with the wire negative the slightest surface imperfection or particle of dust caused a lowering of the value of E. The observations on negative corona were extremely difficult on this account. On raising the voltage the smallest fraction above that required to form corona, the blue glow changed to a purple, point discharge and on lowering the voltage, corona held on to a value of voltage far below that required to start corona. The wire had to be removed and carefully polished again before another observation could be made. With precautions against the above increase of voltage beyond corona value it was possible to repeat the observations on the negative corona as often as desired.

(e) Final methods of taking observations: The final method of taking observations was as follows:- The wire was carefully polished, placed in the tube, accurately centered and connected to the voltage supply. In the alternating current case, the voltage was slowly raised by increasing the generator field current until the electroscope began to discharge. Readings were taken of the rate of leak of the electroscope corresponding to each increment of the voltage until the rate of discharge became practically infinite. The field current was then decreased until the leak of the electroscope ceased and then increased again until visual corona appeared. The voltage was read at this instant on the primary voltmeter and recorded as primary volts. The temperature and pressure were also recorded. The peak factor of alternating voltage waves was determined by means of oscillograms. A large number were taken and from these the values of 1.466 at 40 volts, 1.464 at 50 volts and 1.464 at 60 volts were determined by measurement. In order to give an idea of the conditions of accuracy in making these measurements, the figures in Table 4 are given for one-half wave of the oscillogram corresponding to 60 volts. The curve was carefully traced on co-ordinate paper and 26 ordinates, 1/20 of an inch apart were read off; the height of each ordinate could be read to 1/50 of an inch. The maximum ordinate was 1.43 ins. high and the root-mean-square of all the ordinates was 0.977, which gives a ratio of maximum to effective of 1.464. Similar measurements on the other oscillograms gave the values given above. The average of these three (1.465) was taken as the ratio of maximum

to effective value over the range of 40-60 volts.

TABLE 4

-:-

Oscillogram of the voltage across the low tension terminals of the transformer at 60 volts.

Ordinate Number	Length	$(Length)^2$
1	0	0
2	2.5	6.25
3	5.0	25.00
4	7.0	49.00
5	11.5	132.25
6	15.3	234.09
7	17.8	316.84
8	20.3	412.09
9	22.3	497.29
10	24.2	585.64
11	25.0	625.00
12	26.0	676.00
13	27.0	729.00
14	28.0	784.00
15	28.6	817.96
16	27.0	729.00
17	25.2	635.04
18	23.5	552.25
19	22.7	515.29
20	21.0	441.00
21	17.8	316.84
22	15.0	225.00
23	12.0	144.00
24	8.8	77.44
25	5.2	27.04
26	0.0	0.00

The oscillograms taken at 40 and 60 volts respectively are given in figs. 20 and 21.

In the direct current experiments the procedure was much the same, the high tension voltage however being read directly on the voltmeter in series with the multiplier, no peak factor determination being necessary. In the case of

the negative corona the electroscope curve could not be obtained due to the disadvantage of raising the voltage above corona as noted above and finally, the galvanometer method of detecting the corona was used.

(f) Accuracy of Observations: The accuracy of observation in the case of the alternating current corona was only limited by the accuracy of reading the voltmeter as the observations could be repeated again and again from day to day when correction was made for temperature and pressure, and the other factors entering into the determination of the value of E could be determined to a very small fraction of 1%. The voltmeter could be read to 1/5 of a division at 60 volts or about 1/3 per cent. It is recognized, however, that the accuracy also depended upon the measurements of peak factor on the oscillograms. The method of measuring these has already been outlined and as the value of the peak factor varied only 0.07% over the range of voltage used, it is felt that the measurement of voltage is the limiting factor, as stated above. The accuracy in the continuous current case was also limited by the voltmeter reading and was about 1/3 per cent also.

PICTURES AND DIAGRAMS.

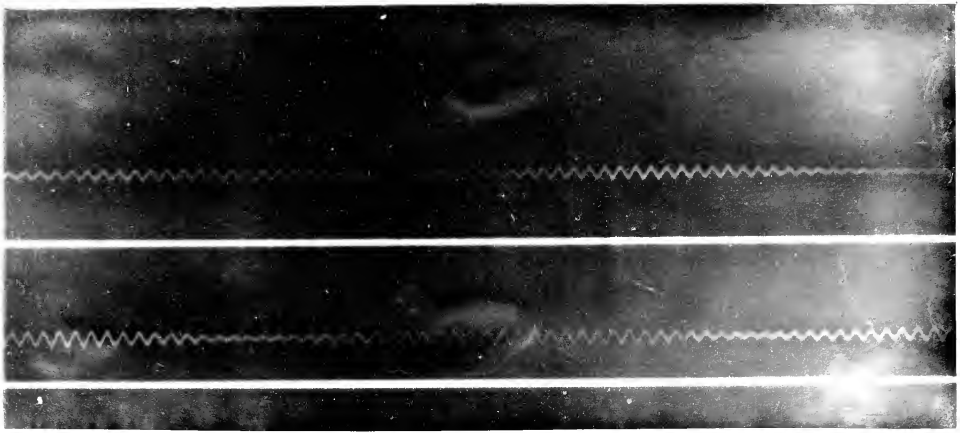


Fig-12

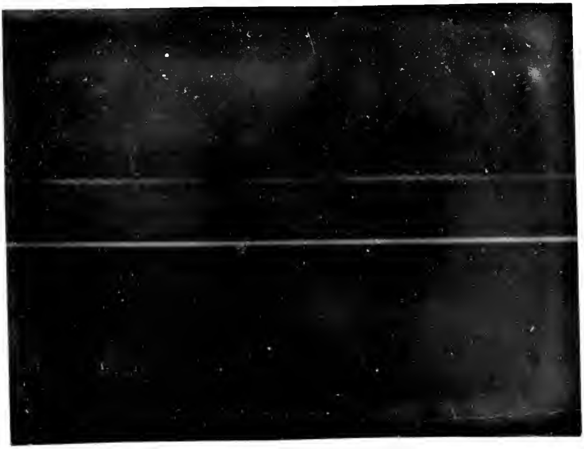
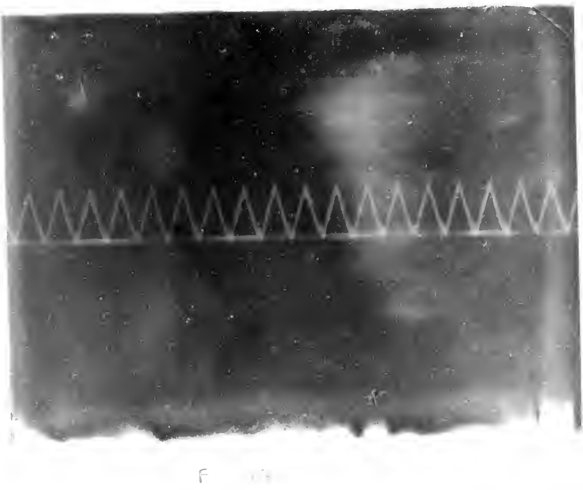


Fig.-13



F

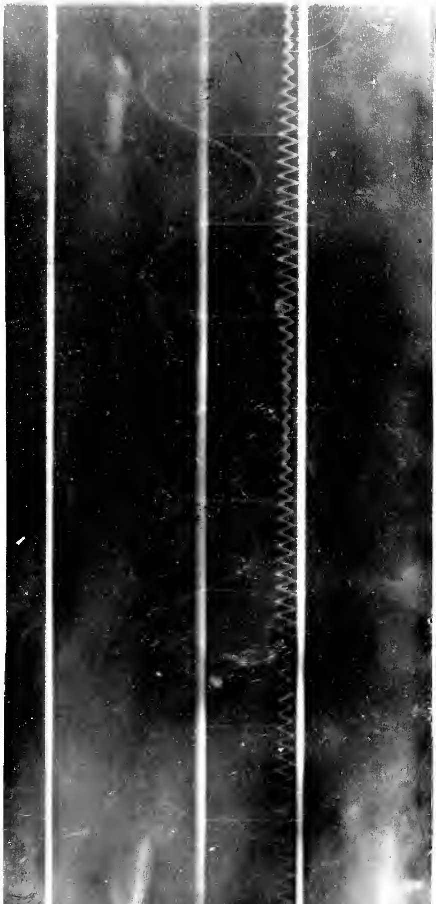
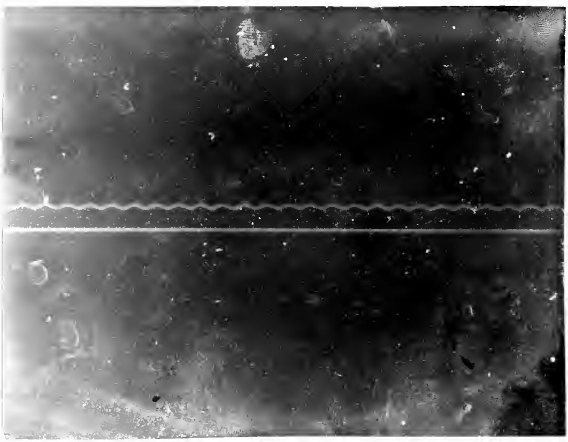


Fig.

Fig. 7



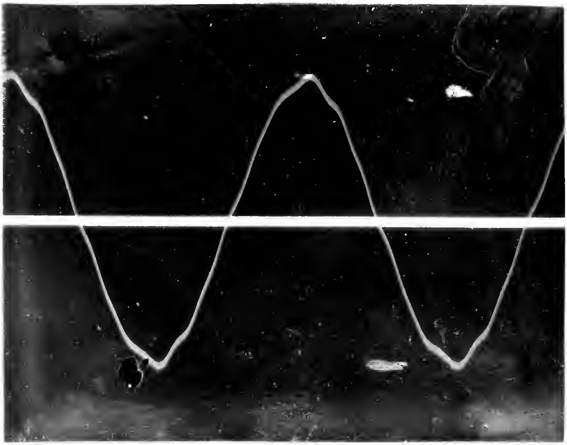
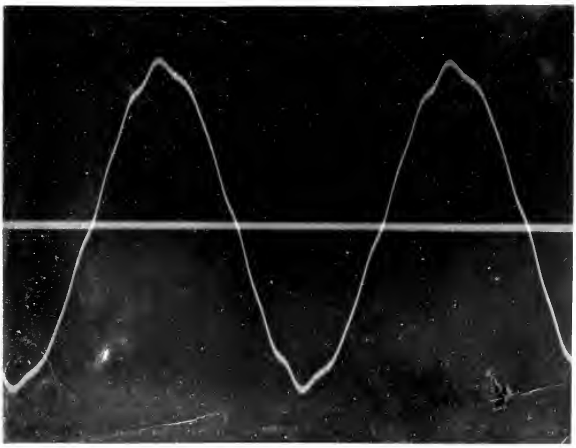


Fig [illegible]



F [illegible]

IV

FINAL EXPERIMENTS

-:-

(1) Relation between critical surface intensity and diameter of the wire for alternating current: In Table (5) are given the results of observations on six sizes of wire in a tube 6.109 cm. in diameter. The first column gives the wire diameter in centimeters, the second column the "density factor", δ, as obtained from Peek's relation

$$\delta = \frac{3.92p}{273+t} \qquad \text{(Formula 4)}$$

and the third column the primary volts. V, the critical voltage (maximum) is obtained by multiplying the primary voltage by the ratio of transformation and the peak factor. The relation

$$E = \frac{V}{a \log_e \frac{b}{a}} \qquad \text{(Formula 1)}$$

was used in calculating the critical surface intensity, E.

The results are limited in number as most of the earlier observations had to be discarded, owing to the use of the potential regulator to control the primary voltage. It was found that the wave shape was dependent on the position of this regulator and as the oscillograms were all taken for one position only, the value of the peak factor was unknown for most of the earlier observations. A large number of runs were made in eliminating experimental difficulties. For any one position of the regulator the readings could be repeated as often as desired. This makes it certain that the accuracy

is much higher than indicated by the number of observations given in Table 5.

(2) <u>Relation between critical surface intensity and diameter of the wire for positive and negative continuous voltage gradient:</u> In Table (6) are given the results of observations on the same wire for positive corona and in Table (7) for negative corona. The first column is again the wire diameter, the second column the density factor calculated from the observed temperature and pressure and the third column the voltmeter reading. The critical voltage, V, is obtained by multiplying the voltmeter reading by the multiplying factor. The last column is obtained as before.

The small number of observations on the negative corona is due to the great difficulty experienced in obtaining them as mentioned before. As many as ten trials with their attendant polishing, centering, etc., were often required to obtain a stable corona. The galvanometer in the grounded circuit proved a great help as the galvanometer only remained on zero up to corona forming voltage when the wire was absolutely clean and if at no time during the run the voltage had been raised above that required to form corona on the given wire.

<u>Determination of the Constants, A and B.</u>

As stated in the introduction the formula connecting E (the critical surface intensity) with the diameter of the wire is of the form,

$$E = A\delta(1 + \frac{B}{\sqrt{r}})$$

where, E = critical surface intensity in kilovolts per centimeter.

δ = density factor

A & B= constants

To determine these constants from the observed results the method of least squares was used. The calculation as applied to the positive corona is given in full in Table (8). Attention is called to the excellent agreement in the observed results and those calculated by the formula. The observed values are given in the third column of Table (8), the calculated values in next to the last column and the percentage error referred to the observed values in the last column. This error is less than 1% with the exception of the wire of radius 0.0535 cms.

Similar calculations were made for the alternating voltage and the negative continuous voltage and the following constants were found.

Positive Corona

A = 33.7 B = 0.241

Negative Corona

A = 31.02 B = 0.308

Alternating Current Corona

A = 33.7 B = 0.266

The values of E for the six sizes of wire calculated from the formula $E = A + \frac{B}{\sqrt{d}}$ using the above constants are given in Tables (9) and (10) and plotted in fig. (22).

In Table (11) is given a comparison of the results of the observations on positive, negative and alternating current corona and the results of the more important previous researches. The formula, $E = A\delta\left(1 + \frac{B}{\sqrt{\delta r}}\right)$ was used in all cases

and the values of the constants A and B as taken from the accounts of the different investigations and used to calculate the values given in Table 12.

TABLE 12

-:-

Type of Voltage	Name of Investigator	Constants A	Constants B
a.c.	Whitehead	32	0.296
a.c.	Peek	31	0.308
d.c.+	Farwell	31.6	0.268
d.c.-	Farwell	35.0	0.230

The values in Table (11) for the alternating current case as plotted in fig. (23), those for the continuous current case (positive and negative) in fig. 24). Inspection of Table (11) and figures (22),(23), (24), shows that

1. Within the range of wires used the corona appears at a lower voltage when the wire is positive than when it is negative.
2. The alternating current values are higher than the positive and lie very near the negative.
3. The curves representing the positive and negative values rapidly converge as the diameter of the wire increases.
4. The results are in accord with the theory of secondary ionization as given by Townsend.
5. The present values of E for the alternating current case differ but slightly from those of Whitehead and Peek.

6. For the positive wire the values of E check those of Farwell, but for the negative wire they are considerably higher.

(c) Discussion

The fact that positive corona appears at a lower voltage than negative for the same size wire is in accord with the theory of secondary ionization if we assume that the negative ion is the principal ionizing agent which is practically certain owing to its energy of motion being greater than that of the positive ion under a given voltage gradient. If a difference of potential be applied between a wire and concentric cylinder the negative ions or electrons present in the air will move under the influence of the field. In so doing they will collide with the molecules of the air and they may or may not produce other ions, depending upon their velocity. Now suppose the wire is positive. In this case the electrons will move inwards (toward the wire) and in so doing will move in the direction in which the intensity of the field is increasing and if the difference of potential between the wire and cylinder be great enough, they will acquire a velocity sufficient to produce ionization by collision with molecules of the gas. The air will then become conducting and a discharge will take place from the wire in the form of corona. On the other hand if the wire is negative, the electrons will move outwards in the direction of decreasing field intensity. Only those which start from near the wire pass through the field of strong electric force so that the number of ions produced by collisions is much smaller than in the first case

or a higher difference of potential will be required to produce enough ions by collision to start corona.

There is an indication of a time element in the formation of the alternating current corona. This is shown by the fact that a higher alternating potential must be impressed on a given wire to produce corona. The alternating wave had a very sharp peak and the rate of recombination of ions is so rapid, it is possible that the duration of the peak voltage is not sufficient to start corona. The alternating voltage must therefore be carried a little higher than the positive continuous voltage to form corona. This of course implies a difference in the value of voltage at which corona forms on the two half-waves of alternating voltage.

There is nothing new in the convergence of the curves for positive and negative corona. Schaffers, Watson, Mackenzie and Farwell all found evidences of this. As the meeting point is a function of the pressure and the diameter of wire it is hard to compare the results of the different investigations on this basis. If the curves for positive and negative corona be extended they will meet at a point corresponding to a wire diameter of 0.285 cms.

Farwell states that the appearance of negative corona changes with increase of wire diameter and voltage, that the negative corona started with a bright spot or two on small wires followed by a continuous brush discharge as the voltage was increased and that for the larger wires the brush discharge appeared immediately upon reaching the critical voltage. By careful polishing and by raising the voltage in very

small steps it was found possible to make the negative corona appear as a continuous, bluish glow on all the wires used. If the voltage was raised the smallest amount above that necessary to produce corona, the bluish glow collapsed to a purplish, point discharge and by lowering the voltage until the discharge just disappeared, a value of E was obtained in close agreement with Farwell. It is believed that this explains to some extent the low values obtained by Farwell in this case.

V

EXPERIMENTS ON CONCENTRIC TUBES.

-:-

(a) Theory of the start of Corona: According to the theory of secondary ionization, if a difference of potential be applied to a tube and concentric wire, the free electrons present in the air between will acquire a velocity under the electric field. The velocity will depend on the applied difference of potential and the "mean free path" of the electron. In order that corona form about the wire it is necessary that the electron acquire a velocity sufficient to produce other ions by collision. If the possible free path of the electron be limited in any way, a higher difference of potential will be required to give the critical velocity to the electron or to produce corona.

(b) Observations and Results: To test this theory concentric insulated tubes were introduced between the wire and corona tube proper in order to reduce the possible free path of the negative ion under the influence of the electric field and to observe the effect of this reduction on the value of V, the maximum value of the voltage required to produce corona. The great difficulty in such experiments is to determine the point at which corona starts when the secondary tube is in place. With the high continuous voltage available it was thought that a galvanometer between the outer tube and the ground would indicate the onset of corona even when the secondary tube was in place, as it had been shown that the galvanometer remained strictly at zero up to corona voltage

and gave a large deflection with the very first appearance of corona.

Accordingly the tube was set up and a second tube supported by three silk threads was inserted between the wire and corona tube proper. On applying continuous voltage to the wire it was found that the voltage could be carried far above that required to start corona when the auxiliary tube was not in place, without the slightest deflection of the galvanometer or indication of any glow about the wire. It was at first thought that this could be explained on the hypothesis that the intermediate tube cut down the number of ionizing electrons already in motion in the outer portion of the field. An electrostatic voltmeter was then connected between the inner tube and the ground and the voltage again applied. The potential of the inner tube as indicated by the voltmeter, when allowance was made for the capacity of the instrument and of the corona apparatus proper, was very closely equal to the theoretical potential at a distance from the wire equal to the radius of the inner tube. An electroscope carrying a charge of known sign showed that the tube was charged to a potential of the same sign as the wire.

The failure of the galvanometer to deflect or of corona to appear was now easily explained as the presence of the high potential of the same sign on the secondary tube lowered the potential gradient between the wire and outer tube and therefore prevents the appearance of corona. That this is the correct explanation was shown by the absence of charge on the inner tube for voltages below corona,

Alternating current was then applied to the wire as it was thought that the inner tube would not acquire the charge noted above. The kenotron was used to rectify the current which flowed from the outer tube to ground through the galvanometer, which was retained in these alternating experiments by reason of its value as a detector. Here again trouble was encountered due to a charge accumulating on the outer tube which disturbed the potential gradient and made it impossible to obtain corona even on raising the voltage far above that required to start corona when the outer tube alone was used and connected direct to ground.

The kenotron is a perfect rectifier and allows current to flow in one direction only. During the half-cycle when the wire is positive a charge of the opposite sign is acquired by the outer tube through the kenotron. During the next half-cycle the wire becomes negative, but a positive charge does not accumulate on the outer tube as the kenotron is conducting in but one direction. The negative charge already there cannot return through the kenotron for the same reason and with each successive half-cycle more and more charge accumulates until the outer tube is considerably above ground potential which lowers the effective potential gradient and prevents the formation of corona.

A vibration galvanometer was next used and after many trials the results shown in Table (13) and plotted in fig. (25) were obtained. The instrument used was of the soft-iron magnet type, in which a piece of soft-iron is suspended by a silk fibre between the poles of a permanent horse-shoe

magnet. A coil carrying the alternating current to be measured produces a field perpendicular to that of the magnet. The temporarily magnetized piece of iron vibrates in synchronism with the alternating current and with an amplitude proportional to the strength of the current. The period of the moving system is adjusted to reconance by a magnetic shunt on the limbs of the magnet.

The first column gives the primary volts. The deflection of the galvanometer was held constant at one centimeter, by varying a non-inductive shunt across the instrument. The values of the shunt used are given in the second column. The total current flowing from the tube at any given voltage on the wire, is given by

$$i = \frac{r_1 + r_2}{r_1} \times i_1 \qquad (17)$$

where, r_1 = resistance of the galvanometer

r_2 = resistance of the shunt

i_1 = current through the galvanometer

As the galvanometer current, i_1 was held constant, equation (17) reduces to

$$i = K \frac{r_1 + r_2}{r_1} \qquad (18)$$

The values of $\frac{r_1 + r_2}{r_1}$ are entered in the last column and the curve (fig. 25) is plotted between $\frac{r_1 + r_2}{r_1}$, which is proportional to the total current flowing and the primary volts on the transformer. The values at which visual corona appeared

with and without this tube, which was 2.448 cm. in diameter, are given in the first line of table (14) and also marked on the curve. Three other tubes were inserted and observations made on the visual corona with and without them. These values are also entered in the table.

TABLE 14

-:-

Effect of thin Concentric Insulated Tubes on Corona Voltage

Diameter Inner Tube Cms.	Primary Volts
2.448	68.7
1.829	69.1
1.209	62.0 (Spark Over)
0.605	---- (Spark Over)
No Tube	64.2

Diam. outer tube = 6.98 cm. Diam. wire = 0.231 cm.

(c) Discussion: The curve (fig. 25) shows that the charging current is higher when the intermediate tube is in place as it should be owing to the increased capacity. The curves follow straight lines up to a value of voltage required to produce corona without the intermediate tube and an indication is given that the corona current rises much more rapidly without the tube which prevents the passage of electrons toward the wire. Corona appears at a higher value of voltage when either of the larger tubes are inserted which is in accord with the theory, as they cut down the number of ionizing electrons already in motion due to the outer portion of the field. If we omit the value obtained for the 1.209

cm. tube which is uncertain owing to spark over, we see that the smaller the diameter of the inner tube the higher the voltage required which again is in accord with the theory as the smaller the inner tube the more the accelerating path is cut down and the higher the voltage required to start corona. Because of the difficulty in maintaining the vibration galvanometer deflection constant as it was affected by the slightest variation in the frequency, further modifications in the direction of constancy of frequency are necessary, and the experiments were terminated at this point. It is believed however that the above results are a reliable qualitative indication that corona voltage is elevated by an intermediate thin screen which serves as a barrier to the free passage of the ionizing electrons.

VI

CONCLUSIONS

-:-

(1) The critical corona forming electric intensity at atmospheric pressure has been determined for six sizes of wire ranging from 0.074 to 0.231 cms. diameter for alternating and continuous potentials, in the same apparatus and under the same conditions.

(2) The relation between critical surface intensity, that is, the intensity at which corona starts, and the diameter of a clean round conductor as found are expressed by the following laws:

Alternating Current*	$E = 33.7\delta\left(1 + \frac{0.266}{\sqrt{\delta r}}\right)$
Continuous Current** (Positive)	$E = 33.7\delta\left(1 + \frac{0.241}{\sqrt{\delta r}}\right)$
Continuous Current*** (Negative)	$E = 31.02\delta\left(1 + \frac{0.308}{\sqrt{\delta r}}\right)$

(3) The observations on the positive and alternating current corona are in substantial agreement with those of Farwell, Peek and Whitehead.

(4) The observations on the negative corona give values higher than any heretofore obtained.

---

*(See Table 9 and Fig. 22)

**(See Table 10 and Fig. 22)

***(See Table 10 and Fig. 22)

(5) Experiments with concentric insulated tubes indicate that the critical corona forming intensity is raised by their introduction. (See Table 14 and Fig. 25)

(6) The results of the present investigation are in accord with the theory of secondary ionization as proposed by Townsend.

This investigation was carried out in the Laboratory of Electrical Engineering of the Johns Hopkins University under the direction of Dr. J. B. Whitehead, Professor of Electrical Engineering. The author wishes to express his sincere appreciation of the assistance rendered him by Mr. M. W. Pullen, Mr. Styers, machinist and Mr. Skrivan, electrician. Particular thanks are due to Dr. W. B. Kouwenhoven who has made many valuable suggestions during the course of the investigation.

TABLE 5

-:-

Alternating Current

Diam. Wire Cms.	Density Factor δ	Primary Volts	Crit. Voltage (Max) V	Crit. Surf. Intensity E(k.v.)
0.074	1.005	35.8	13120	80.6
	1.005	35.8	13120	80.6
	1.005	35.8	13120	80.6
0.090	1.005	39.65	14530	77.1
	1.005	39.65	14530	77.1
	1.005	39.65	14530	77.1
0.107	1.005	42.85	15700	72.6
	1.005	43.05	15780	73.0
	1.005	43.20	15830	73.2
0.125	1.005	45.6	16700	68.8
	1.005	45.65	16720	68.9
	1.005	45.7	16750	69.0
0.166	1.005	53.5	19610	65.6
	1.005	53.5	19610	65.6
	100 5	53.5	19610	65.6
0.231	1.005	61.4	22500	59.6
	1.005	61.4	22500	59.6
	1.005	61.4	22500	59.6
0.231	1.000	64.2	23520	59.7
	1.000	64.2	23520	59.7
	1.000	64.2	23520	59.7

TABLE 6

-:-

Positive Corona

Diam. Wire Cms.	Density Factor δ	D.C.Volts	Mul.Fac.	Crit.Voltage (V)	Crit.Surf Int. (E)
0.074	1.02	228.0	52.18	11897	77.0
	1.02	227.5	52.18	11871	76.9
	1.02	228.0	52.18	11897	77.0
	1.00	558.0	19.83	11660	75.5
	1.00	587.5	19.83	11650	75.4
	1.00	587.5	19.83	11650	75.4
	1.022	227.5	52.18	11871	77.1
	1.022	227.5	52.18	11871	77.1
	1.022	227.5	52.18	11871	77.1
	1.035	442.5	28.36	12549	77.1
	1.035	443.0	28.36	12560	77.2
	1.035	443.0	28.36	12560	77.2
0.090	1.01	657.5	19.83	13038	72.8
	1.01	657.5	19.83	13038	72.8
	1.01	657.5	19.38	13038	72.8
	1.02	665.0	19.83	13187	73.6
	1.02	665.0	19.83	13187	73.6
	1.02	665.0	19.83	13187	73.6
	1.007	637.5	19.83	13038	72.8
	1.007	637.5	19.83	13038	72.8
	1.007	637.5	19.83	13038	72.8
	1.02	665.0	19.83	13187	73.6
	1.02	665.0	19.83	13187	73.6
	1.02	665.0	19.83	13187	73.6
	1.005	657.5	19.83	13038	72.8
	1.005	657.5	19.83	13038	72.8
	1.005	657.5	19.83	13038	72.8
	0.998	654.0	19.83	12969	71.4
	0.998	654.0	19.83	12969	71.4
	0.998	654.0	19.83	12969	71.4
	1.025	253.0	52.18	13200	73.7
	1.025	253.0	52.18	13200	73.7
	1.025	253.0	52.18	13200	73.7
0.107	1.022	275.0	52.18	14350	69.2
	1.022	275.0	52.18	14350	69.2
	1.022	275.0	52.18	14350	69.2
	1.035	533.0	28.36	15116	69.9
	1.035	532.5	28.36	15102	69.8
	1.035	533.0	28.36	15116	69.9

TABLE 6

-:-

Positive Corona

Diam. Wire Cms.	Density Factor δ	D.C.Volts	Mul.Fac.	Crit.Voltage (V)	Crit.Surf. Int. (E)
0.125	1.008	292.5	52.18	15263	66.8
	1.008	292.5	52.18	15263	66.8
	1.008	292.5	52.18	15263	66.8
0.116	1.003	357.5	52.18	18654	62.4
	1.003	357.5	52.18	18654	62.4
	1.003	357.5	52.18	18654	62.4
0.231	1.02	422.5	52.18	22046	58.4
	1.02	422.5	52.18	22046	58.4
	1.02	422.5	52.18	22046	58.4

TABLE 7

-:-

Negative Corona

Diam. Wire Cms.	Density Factor	D.C.Volts	Mul.Fac.	Crit.Volt-age (V)	Crit.Surf. Int. (E)
0.074	1.003	462.5	28.36	13117	80.6
	1.003	462.5	28.36	13117	80.6
	1.003	462.5	28.36	13117	80.6
0.090	1.03	517.0	28.36	14662	77.8
	1.03	517.5	28.36	14676	77.9
	1.03	517.0	28.36	14662	77.8
	0.9907	503.0	28.36	14265	75.6
	0.9907	502.5	28.36	14230	75.6
	0.9907	503.0	28.36	14265	75.6
0.107	1.003	560.0	28.36	15880	73.5
	1.003	560.0	28.36	15880	73.5
	1.003	560.0	28.36	15880	73.5
0.125	0.992	587.0	28.36	16657	68.6
	0.992	587.0	28.36	16657	68.6
	0.992	587.0	28.36	16657	68.6
0.166	1.003	667.5	28.36	19214	64.3
	1.003	667.5	28.36	19214	64.3
	1.003	667.5	28.36	19214	64.3
0.231	1.001	431.0	52.18	22440	59.3
	1.001	431.0	52.18	22440	59.3
	1.001	431.0	52.18	22440	59.3

CALCULATION OF CONSTANTS A AND B

-:-

(Positive Corona)

Method of Least Squares:-

$$E = A\delta\left(1 + \frac{B}{\sqrt{\delta r}}\right) = A\delta + C\sqrt{\frac{\delta}{r}}$$

where,

E = critical surface intensity in k.v. per cm.

δ = density factor

r = radius wire in cm.

A & B = constants

C = constant

$\Sigma\left(E - A\delta - C\sqrt{\frac{\delta}{r}}\right)^2$ is to be a minimum

Differentiate with respect to A

$$\Sigma\delta E - A\Sigma\delta^2 - C\Sigma\sqrt{\frac{\delta^3}{r}} = 0 \qquad (1)$$

Differentiate with respect to C

$$\Sigma\sqrt{\frac{\delta}{r}}\,E - A\Sigma\sqrt{\frac{\delta^3}{r}} - C\Sigma\frac{\delta}{r} = 0 \qquad (2)$$

Substituting in equations (1) and (2) the values of $\Sigma\delta E$, $\Sigma\delta^2$, $\Sigma\sqrt{\frac{\delta^3}{r}}$, $\Sigma\sqrt{\frac{\delta}{r}}$, $\Sigma\frac{\delta}{r}$. from accompanying table, we have

$$6.198A + 25.235C = 414.28 \qquad (3)$$

$$25.235A + 106.620C = 1718.21 \qquad (4)$$

Solving for A and C

$A = 33.7$ $\qquad$ $C = 8.13$

$$E = 33.7\delta + 8.13\sqrt{\frac{\delta}{r}} = 33.7\delta\left(1 + \frac{0.241}{\sqrt{\delta r}}\right)$$

$A = 33.7$ $\qquad$ $B = 0.241$ for positive corona

TABLE 8

-:-

Calculation of Constants A and B

(Positive Corona)

r	δ	δ^2	δ^3	$\frac{\delta^3}{r}$	$\sqrt{\frac{\delta^3}{r}}$	$\frac{\delta}{r}$
0.037	1.02	1.0404	1.061	28.68	5.375	27.77
0.045	1.025	1.0506	1.076	23.9	4.885	22.7
0.0535	1.022	1.0445	1.068	19.97	4.47	19.14
0.0625	1.008	1.0161	1.025	16.4	4.05	16.12
0.083	1.003	1.0060	1.01	12.16	3.85	12.07
0.1155	1.02	1.0404	1.061	9.19	3.03	8.82
Σ		6.198			25.235	106.62

r	E Obs.	δE	$\sqrt{\frac{\delta}{r}}$	$\sqrt{\frac{\delta}{r}}E$	E Calc.	Error %
0.037	77.0	78.54	5.27	405.79	77.1	-0.13
0.045	73.7	75.54	4.765	351.18	73.4	+0.41
0.0535	69.2	70.72	4.375	302.75	70.0	-1.1
0.0625	66.8	67.33	4.015	268.2	66.7	+0.14
0.083	62.4	62.59	3.475	216.84	62.1	+0.48
0.1155	58.4	59.56	2.97	173.45	58.5	-0.17
Σ		414.28	24.87	1718.21		

TABLE 9

-:-

Alternating Current

Relation between Diameter and Critical Surface Intensity

Diam. Wire Cms.	Density Factor δ	Primary Volts	Crit. Voltage (Max) V	Crit.Surf. Intensity E(k.v.)
0.074	1.005	35.8	13120	80.6
0.090	1.005	39.65	14530	77.1
0.107	1.005	43.0	15760	72.9
0.125	1.005	45.7	16750	69.0
0.166	1.005	53.5	19610	65.6
0.231	1.005	61.4	22500	59.6

TABLE 10

-:-

Continuous Current

(Positive)

Relation between Diameter and Critical Surface Intensity

Diam. Wire Cm.	Density Factor δ	Voltmeter Reading	Critical Voltage (V)	Critical Surface Intensity (E) (k.v.)
0.074	1.02	228.0	11897	77.0
0.090	1.025	253.0	13200	73.7
0.107	1.022	275.0	14350	69.2
0.125	1.008	292.5	15263	66.8
0.166	1.003	357.5	18654	62.4
0.231	1.02	422.5	22046	58.4

(Negative)

Diam. Wire Cm.	Density Factor δ	Voltmeter Reading	Critical Voltage (V)	Critical Surface Intensity (E) (k.v.)
0.074	1.003	462.5	13117	80.6
0.090	1.03	517.0	14662	77.8
0.107	1.003	560.0	15880	73.5
0.125	0.992	587.0	16657	68.6
0.166	1.003	677.5	19214	64.3
0.231	1.001	431.0	22490	59.3

TABLE 11

-:-

Comparison of Results

	Alternating Current			Continuous Current			
Diam. Wire Cm.	White-head	Peek	Brown	Brown +	Farwell +	Brown -	Farwell -
0.074	81.2	80.7	80.3	76.0	75.7	80.8	76.9
0.090	76.6	76.0	76.0	71.9	71.6	76.1	72.9
0.107	72.9	72.3	72.5	68.9	68.3	72.4	69.8
0.125	69.9	69.2	69.6	66.2	65.5	69.3	67.2
0.166	64.8	64.1	64.8	61.9	61.1	64.2	62.9
0.231	59.9	59.1	60.1	57.6	56.6	59.1	58.7

TABLE 13

-:-

Effect of Concentric Tubes

(With Inner Tube)

A.C. Volts	Shunt in ohms	$\frac{r_1 + r_2}{r_1}$
40.0	11.0	3.78
45.0	10.0	4.06
50.0	9.0	4.4
55.0	8.5	4.605
60.0	7.5	5.08
65.0	7.0	5.34
67.5	6.0	6.1
70.0	5.0	7.12
72.5	3.0	11.2

(Without Inner Tube)

A.C. Volts	Shunt in ohms	$\frac{r_1 + r_2}{r_1}$
40.0	12.0	3.55
45.0	11.0	3.78
50.0	10.0	4.06
55.0	9.3	4.30
60.0	8.7	4.52
62.5	8.3	4.69
65.0	7.6	5.03
66.0	6.5	5.71

Galvanometer Deflection constant = 1 cm.

Visual Corona with tube = 69.1

Visual Corona without tube = 64.2

VII

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V I T A

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